Proxemy Research Technical Report #TOPO-00-012

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Title: 2000 Annual Report: 'Topographic Effects on Geologic Mass Movements'

Submitted to: Dr. Herbert Frey/COTR
Code 921
NASA GSFC

March 31, 2000

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Proxemy Research is under contract to NASA to perform science research on the effects of topography on geologic mass movements. The current project concentrates on the sensitivity of lahars and debris flows to various scales of topographic variability. The following report constitutes delivery of ***Milestone Event #12*** under NASA contract NAS5-99182.

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1. Introduction

Funding for this project began in April 1999. Since the project's inception, we have completed all milestones established in contract NAS5-99182. Monthly progress reports have been submitted, detailing work accomplished over each time period. This final report documents and summarizes the results of the entire project, including conclusions based on our findings and recommendations for further investigation.

Proxemy's efforts towards fulfilling these tasks has been divided into two areas, theoretical investigation and applications to actual mass movements. The theoretical investigation focused on determining differences in flow thicknesses and advance rates when the mass movements flow over topography with variability and roughness at different scales. Here we have used both steady-state and time-dependent models. We have also applied these models to actual lahars at Mt Ruapehu, New Zealand. The applications have also included a major collaborative effort with Dr. Mark Bulmer (CEPS/NASM) to collect and analyze appropriate data from the recent debris flows in Madison County, Virginia.

The research progress for each of the monthly milestones is summarized below. Details of the data products and scientific analyses appear as Appendices. In conclusion, we summarize the scientific progress achieved by this effort and identify promising areas of future research.

2. Summary of Milestone 1

The initial efforts were focused on background investigations of well-documented lahars and similar mass movements at Mt. Ruapehu and Mount St. Helens. The goal was to begin compiling data for evaluating the sensitivity of mass movements to topographic variations and identify where the data sets were incomplete.

3. Summary of Milestones 2, 3, and 4

These milestones addressed a theoretical estimation of the sensitivity of rapid mass movements to variations in topography. A simple quantitative model was derived for lahar propagation assuming an empirical flow rate law, local and global conservation of flow, constant coefficient of resistance, and steady-state conditions. Such restrictions make the flow respond only locally to topography variability. This elementary model was applied to a number of simulated topographies with identical average dimensions (elevation loss of 10 km over a 30 km length) but widely varying local slopes. The topography was simulated by superimposing sinusoidal forms of varying amplitudes and cycles to a uniformly sloping plane. The results show that both thicknesses and flow front arrival times for identical average topographies are highly dependent upon local topographic elements. In particular, the presence of irregularities in the slope can significantly slow the lahar. Flow front arrival times were seen to increase with increasing amplitudes and increasing cycles. This effect was considerably greater than that expected by increased travel distances along the curve of the roughened topography. These results show the importance of fine-scale topographic data for accurate prediction of hazards from lahars, debris flows, and similar mass movements.

4. Summary of Milestones 5, 6, and 7

A new time-dependent model for lahar transport was derived based on local and global conservation of volume for a commonly used empirical flow rate. The time-dependent solutions for the thickness profile contain a term for cumulative topographic influence. This previously unrecognized cumulative effect arises from three factors: nonlinearity in the local flow rate, topographic changes along the path of the flow, and time-dependence in the longitudinal thickness profile. This model was compared to the steady-state model using identical underlying topographies. The topographic profiles and the arrival times were shown to be dramatically different when time-dependence was included. This, in turn, amplifies the need for topographic data at scales comparable to the thickness of the lahar or debris flow.

Proxemy Research personnel also began supporting an ongoing field investigation of the 1995 debris flows at Madison County, Virginia, by Dr. Mark Bulmer (CEPS/NASM). Efforts during this period were directed toward field measurements of topography using GPS and laser ranging. Proxemy personnel were active in the acquisition of longitudinal and transverse channel profiles for one of the primary debris flows that occurred in 1995.

5. Summary of Milestones 8, 9 and 10

As part of a general field investigation of the Generals Landslide in Madison County, Virginia, a high-resolution topographic data set was and compiled, including field interpretations by CEPS and Proxemy Research. The initial results from this effort were presented at the East Coast Volcanologists' Meeting at CEPS during November, 1999. Results with potential planetary applications were written up in an abstract submitted to the Lunar and Planetary Science Conference (Appendix 1.A). Preliminary results from the Madison debris flow investigation were presented during a poster session at the Lunar and Planetary Science Conference (see Appendix 2).

6. Summary of Milestone Event 11

Research activities focused on mass movements of the Cascade volcanoes. Topographic data for Mount St. Helens and Mount Rainier were obtained from USGS DEMS. A commercial software package ("Topo!") was used to characterize the slopes at Mount Rainier, while cross-sectional areas for a number of historic mass movements were obtained from a USGS Professional Paper (#1547).

Work also continued on the Madison County debris flow field site. The initial flow modeling results had proven unsatisfactory, as large, unexplained variations in rheology appeared to exist. Numerous meetings were held to develop interpretations of the field data compatible with the context of a theoretical model. Agreement was reached on all interpretations and reasonable alternatives for the dimensions of the flow. We now consider the compiled data set for the Generals Landslide to be state-of-the art for a debris flow that was largely unobserved. This data set appears as Appendix 1. The modeling efforts were reapplied with satisfactory results. A draft manuscript for publication in Geophysical Research Letters was also begun (see Appendix 4).

7. Summary of Milestone Event 12

Significant effort was devoted toward the documentation of the data set and field interpretations for the Generals Landslide. Similar efforts were directed toward obtaining similar comprehensive data sets for mass movements at Mt. Ranier and Mt. St. Helens from the literature and other sources. An abstract for follow-on work was submitted to the American Geophysical Union for the Spring 2000 meeting (see Appendix 3). Contributions to the draft GRL manuscript were made and effort was devoted to the final documentation of this project.

8. Conclusions

The final year of this project has been productive. Theoretical models have been developed for application to lahars, debris flows, and other geologic mass movements. These models have been formulated to be used in conjunction with field and remote sensing data. Using these models, we have investigated the effects of topography at a variety of scales on the emplacement velocity and flow profiles of lahars and debris flows. We have applied one of these models to a small, well-documented debris flow and have interpreted the results in the context of a general field investigation.

We have shown that topographic resolution can significantly affect emplacement velocity, flow thicknesses, and estimates of flow rheology. We have also demonstrated that using interpolated slope values derived from regression fits for high resolution data yields modeling results more reliable than those obtained with either low or high resolution topographic data.

One future activity will be to apply the time-dependent model to the data sets for the Generals Landslide and similar mass movement at Mt Rainier and Mt St Helens. This effort should lead to a greater understanding of the time-dependent effects of topography on flow emplacement and provide improved assessments of hazards.

This research has produced two abstracts, a draft manuscript which will be submitted to Geophysical Research Letters in the near future, a state-of-the art debris flow data set, numerous formal and information presentations, and theoretical advances in understanding the sensitivity of rapid mass-movements to variations in topography.

APPENDIX 1:

Investigation Methodology and Compiled Data for the Generals Debris Flow in Madison County, Virginia

APPENDIX 1.A:

LPSC Abstract

APPENDIX 2:

LPSC Poster

APPENDIX 3:

AGU Abstract

APPENDIX 4:

Draft GRL Manuscript

APPENDIX 1: INVESTIGATION METHODOLOGY AND COMPILED DATA FOR THE GENERALS DEBRIS FLOW IN MADISON COUNTY, VIRGINIA

Introduction:

Detailed field studies of mass movements such as debris flows, lahars, and mudflows are essential for interpreting data in the context of theoretical emplacment models. To this end, Proxemy Research personnel have participated in a GPS field survey of the Generals Landslide in Madison County, Virginia, headed by Mark Bulmer of the Smithsonian Institution's Center for Earth and Planetary Studies (CEPS). The elevation of the main channel was surveyed in detail to obtain the slope of the debris flow and information about the roughness of the channel. In addition, 10 transects were made across the channel at various stations along the flow path. The transect positions are overlayed on an air photo in Figure 1. The modeling data derived from the field survey (transect name, position, elevation, and slope; minimum and maximum width, area, and thickness) is given in Table 1. Additional information describing the transects is summarized in Table 2.

Field survey:

The main channel of the "General slide" was surveyed using a Trimble Total Station 4800, which consists of two GPS receivers that work in tandem. This equipment uses carrier-phase differential processing for 1 cm horizontal real-time accuracy. One receiver remains fixed on a tripod at a known location during the survey. The location of this receiver was determined to an accuracy of 1-2 m using a Trimble ProXRS GPS unit using satellite-based differential correction. This base station was then used as the reference point for all subsequent surveys. The roving Trimble 4800 receiver used for data collection is mounted on a pole 1.8 m in length. This pole allows the survey team to determine positions even in the small spaces between blocks, so the topography can be adequately characterized. A radio link, provided by a 25 W UHF radio at the base station, is constantly maintained for real-time differential correction. While conducting transects up the main channel, a 3-D point (elevation and position) was collected approximately every 3 m. For the transect up the channel (transect 1) we obtained 1 cm horizontal and 2 cm vertical accuracy per point to about 1000 m up from the lower end of the channel, until we encountered difficulties in satellite coverage due to screening by the tree canopy. Beyond that point, the accuracy was only about 20-40 cm. We successfully collected data up to the top of the main channel, about 1600 m. The data points are shown in a scattergram (Figure 2).

Slope algorithm:

The elevation data obtained during the field survey were plotted as functions of downstream distance (Figure 3). A third-order polynomial regression was then applied to this data to derive a characterization function for the elevation, (Z) as a function of distance (X):

$$Z = 5.617 \times 10^{-8} X^3 + 2.544 \times 10^{-4} X^2 - 0.472968\ X + 613.03$$

A gradient function was then obtained from the derivative of the elevation function:

$dZ/dX = 16.851 \times 10^{-8} X^2 + 3.088 \times 10^{-4} X - 0.472968$

Slopes were then calculated at each transect position from:

$\theta = \arctan (dZ/dx)$

Issues: Minimum and Maximum parameter values from field data

Under actual field conditions, defining the shape of the active flow lobe from the remaining evidence proved a non-trivial task. Depth markers such as scars on trees and debris piles were used as indicators of both depth and position of the flow edge. However, in some cases the geomorphic evidence was absent or inconclusive. Air photos of the site taken immediately following the event proved useful supplements, but yielded direct information only on the channel and deposit, and not the active lobe itself. There was considerable evidence for superelevation, with markers indicating that flow depths on one bank may well have exceeded those on the opposite bank. Thus, it was not possible to absolutely constrain the dimensions and position of the active flow. Instead, minimum estimates (based on a horizontal flow surface at the lowest depth) and maximum estimates (assuming a "tilted" flow surface between depth indicators) were used to constrain the dimensions, with the actual values most likely falling between these two extremes. The transects, with minimum and maximum flow surfaces, are illustrated in Figure 4. For comparative purposes, the cross-sections are plotted at same scale in Figure 5.

Cross-sectional area and thickness algorithm:

To estimate the minimum cross-sectional area from the transect data (Figures 4 and 5), Each flow transect is divided into segments (Figure 6a). Each data point is the right edge of one segment and the left edge of the next (except for endpoints). The width of the segment is then the distance between the two data points that make the edges. The segments are treated as rectangles; average elevation of the bottom is calculated from an unweighted average of the two edge points. Depth is found by subtracting this elevation from the assumed elevation of the flow surface. The contribution of each segment to area is then the segment width times this depth; these are summed to estimate cross-sectional area for the entire transect.

The average thickness for the cross-section is found from the area divided by the width; effectively, a weighted mean. Thus the wider the segment, the more its depth is considered in the determination of the average.

The method for determining maximum areas is basically the same, only the elevation of the top of each segment, instead of being the same horizontal flow level, is extrapolated from a linear equation, assuming a tilted straight-line superelevated flow surface. For each segment we calculate an average flow level between the two end points, assume the flow is "stepping up" and thus flat across the top, and find the thickness of the segment column from the difference between this elevation and the average elevation of the bottom--again dividing the flows into rectangles, but now each rectangle has its own top (Figure 6b).

The Generic Empirical Rheology Model

The initial model applied to the Generals debris flow data assumes steady-state flow volume conservation and a flow rate of the form:

$$Q = uA = \left(\frac{g\sin\theta h}{C}\right)^k A \tag{1}$$

where A is the cross-sectional area of the flow, C and k are empirically-derived parameters, and u is the local flow velocity. By conservation,

$$Q_0 = \left(\frac{g\sin\theta_0 h_0}{C_0}\right)^k A_0 = \left(\frac{g\sin\theta_n h_n}{C_n}\right)^k A_n = Q_n \tag{2}$$

Solving for C, the flow resistance coefficient, yields:

$$\left(\frac{C_n}{C_0}\right) = \left(\frac{A_n}{A_0}\right)^{1/k} \left(\frac{\sin\theta_n h_n}{\sin\theta_0 h_0}\right) \tag{3}$$

Given measurements of cross-sectional area, thickness, and slope, as well as a value for k, this equation can be used to calculate relative changes in rheology from some initial point. The typical value k =0.5, employed in numerous previous studies, is adopted as a mathematical convenience. However, initial attempts to estimate k imply that the value for the Generals slide is somewhere in this vicinity. C_n/C_0 values are given in Table 1 under "Modeling results". Initial results from the application of this model are discussed in Bulmer et al. (Appendix 4).

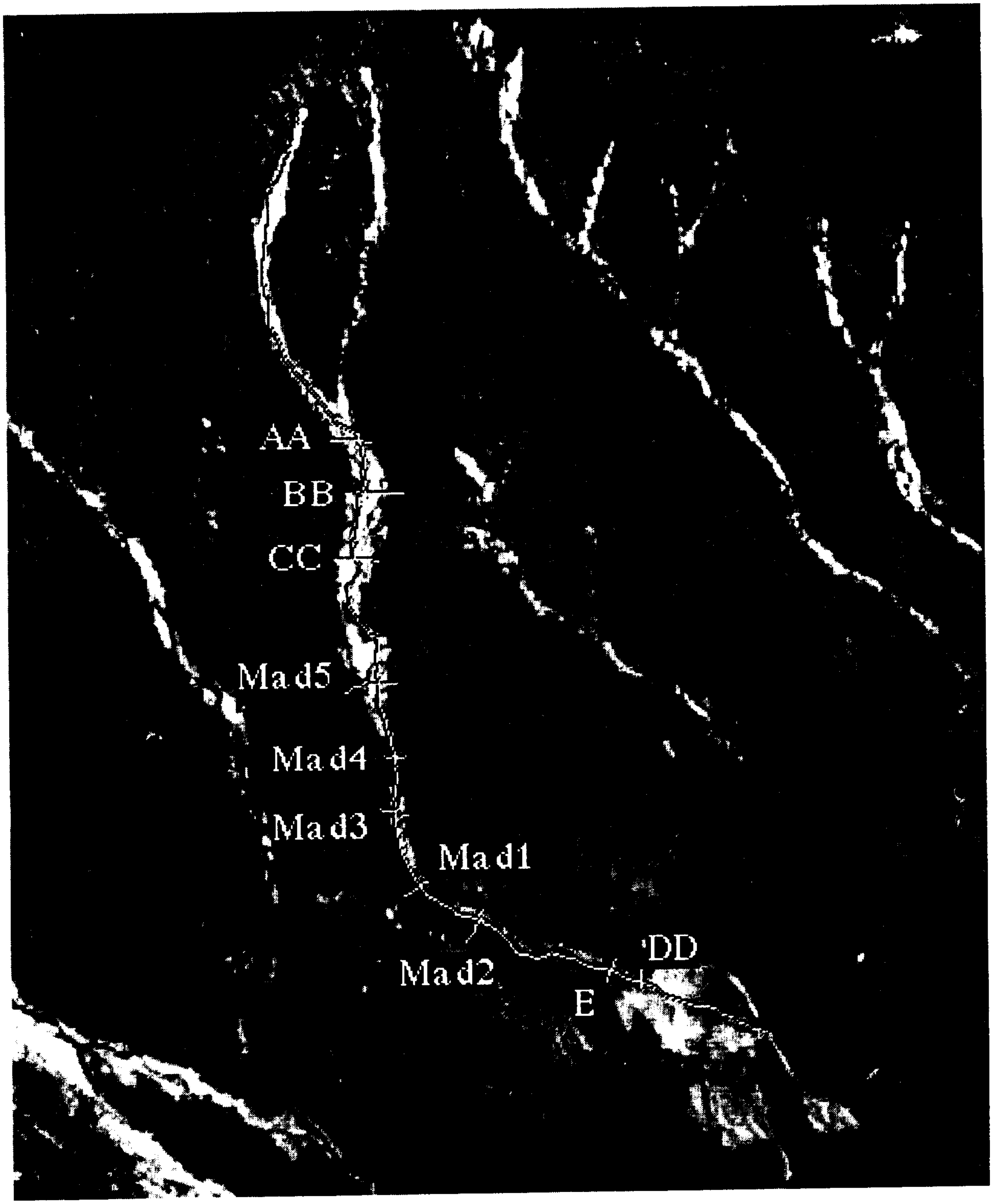
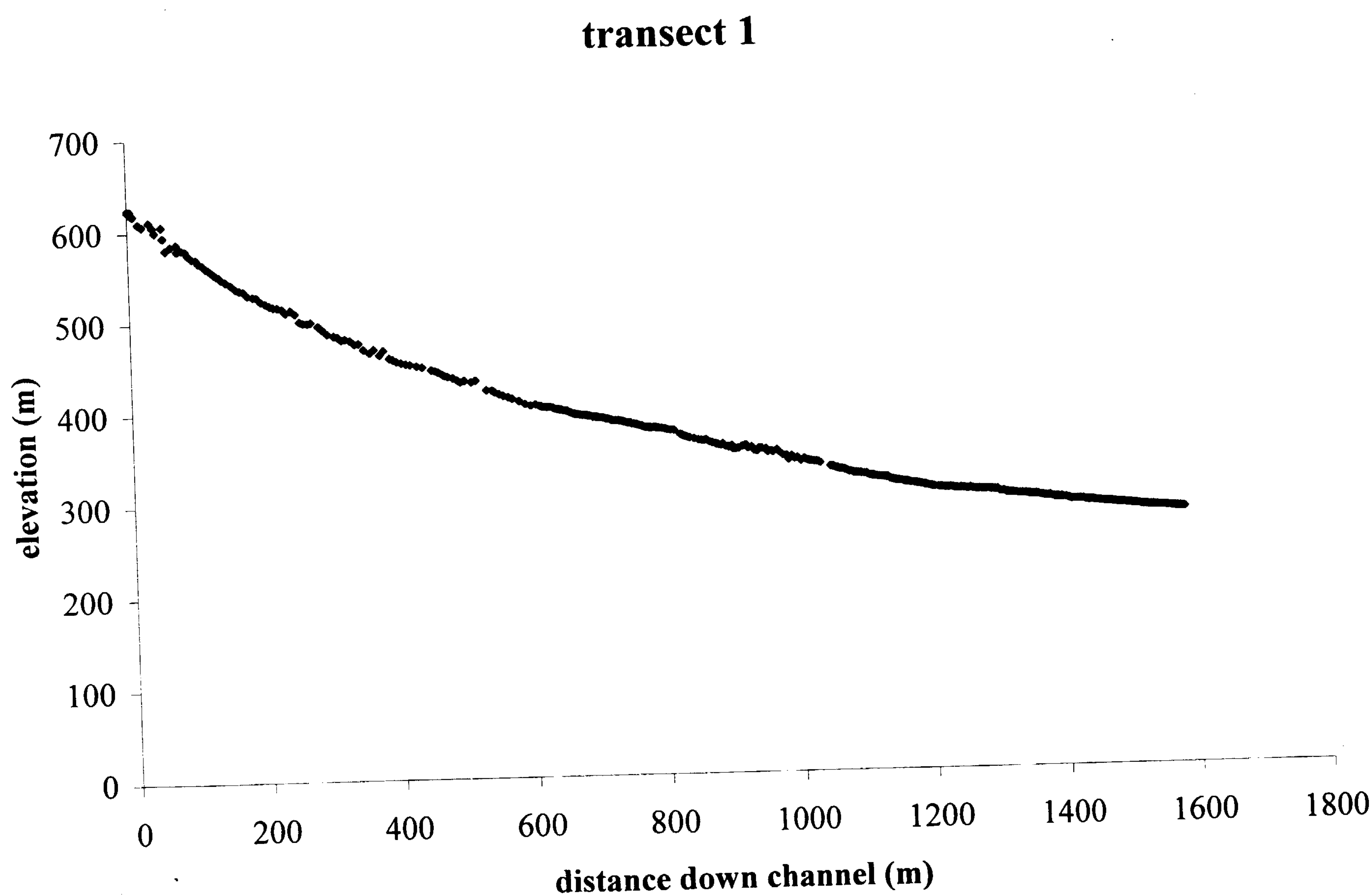


Figure 1

App 1

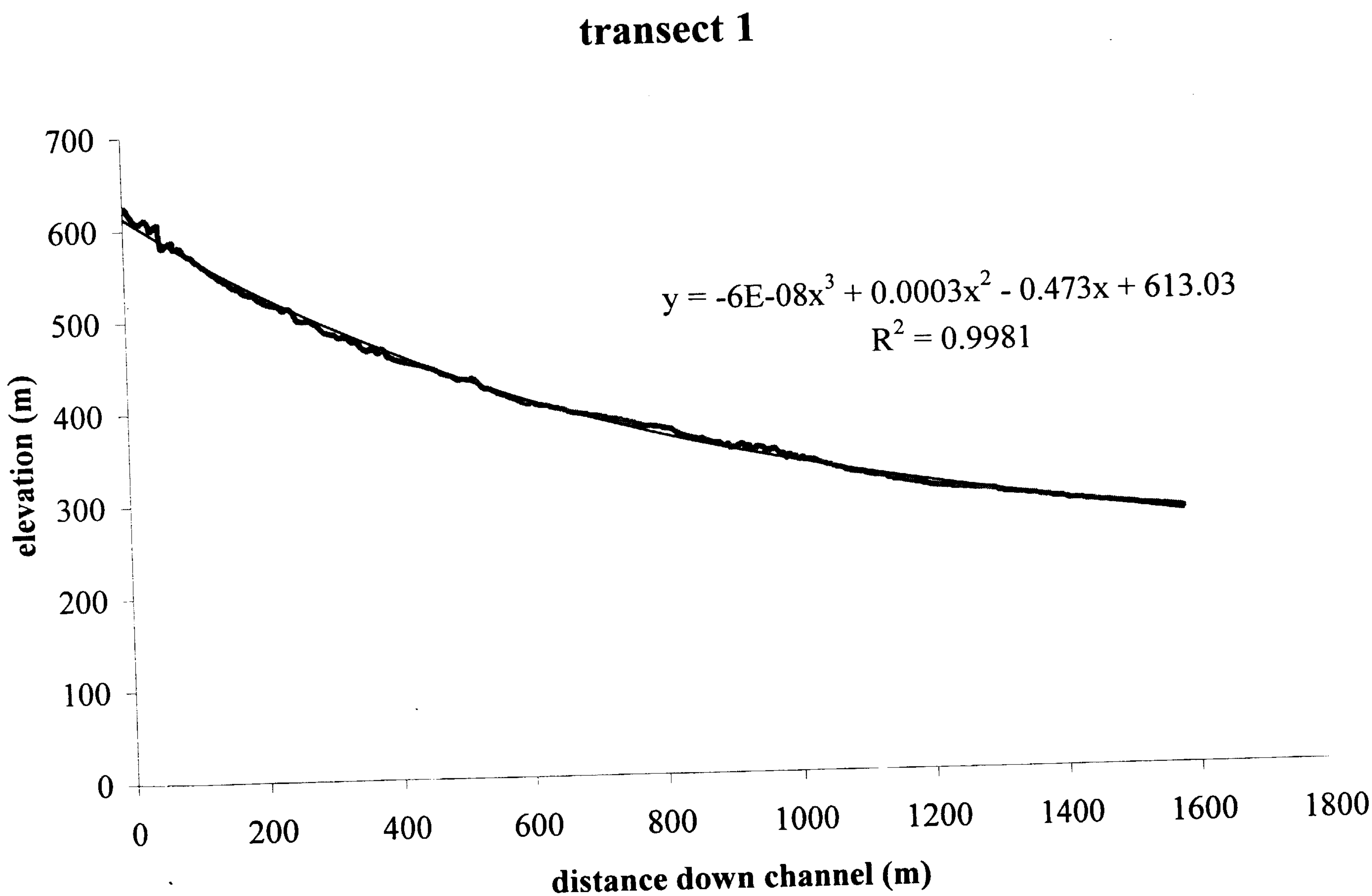


APP 1

Figure 2

Data

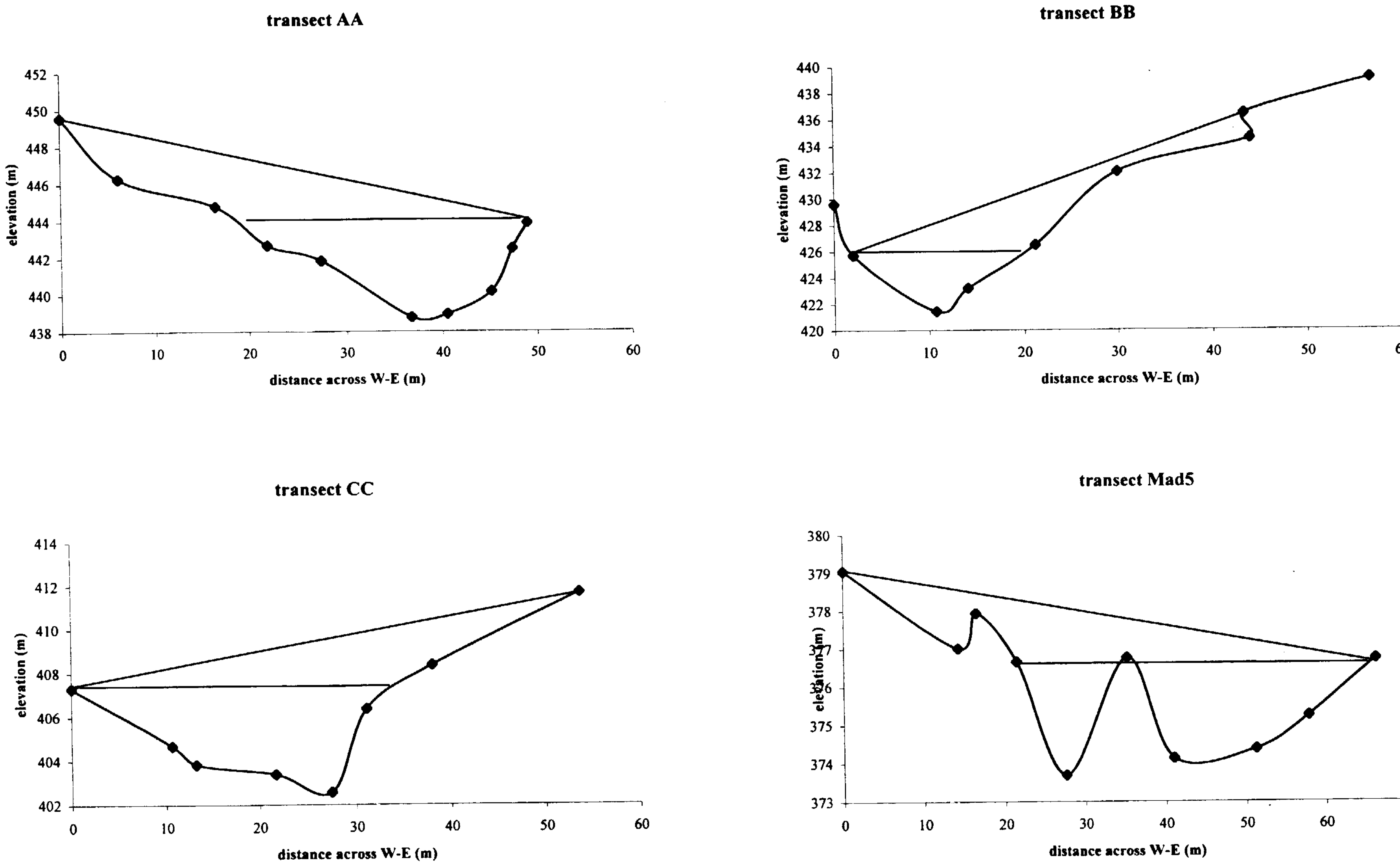
Generals Slide: Main Channel



App. I

Figure 3

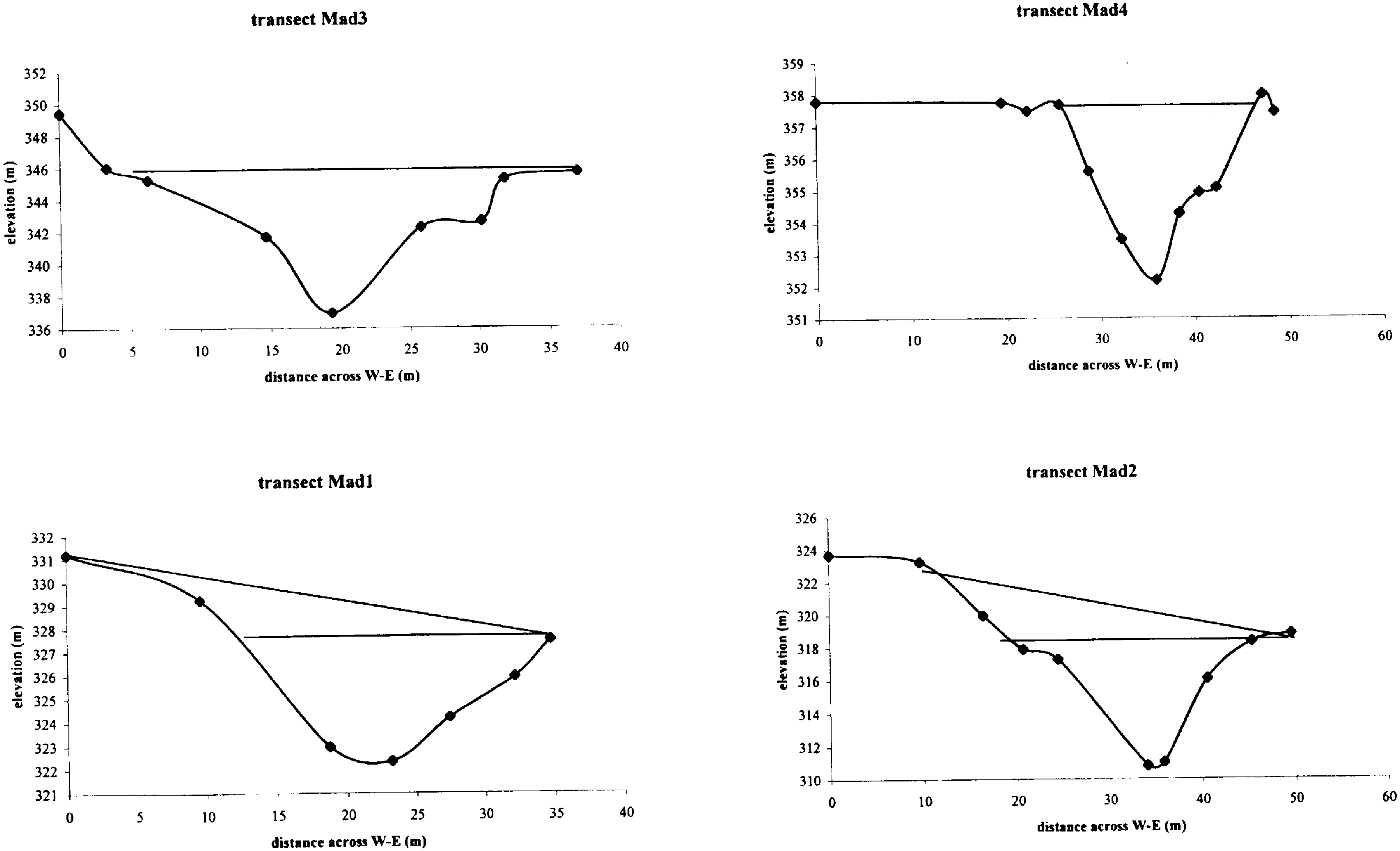
Generals Slide: Main Channel



APP. 1

Figure 4a

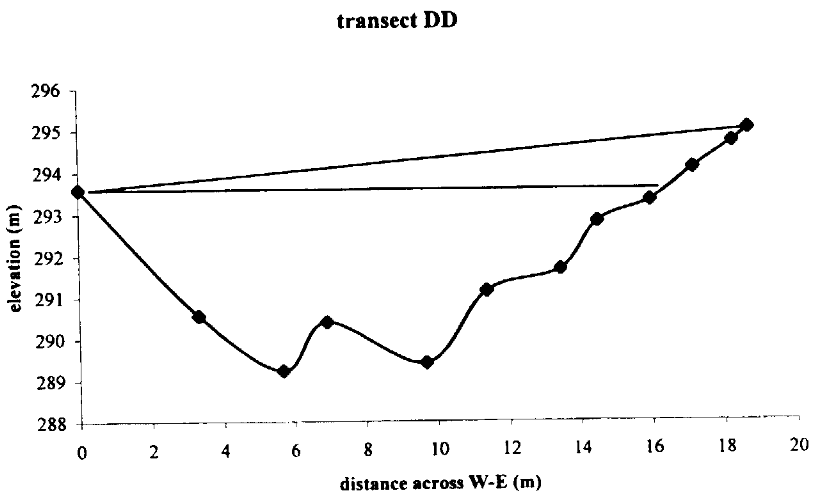
Generals Slide Cross-sections

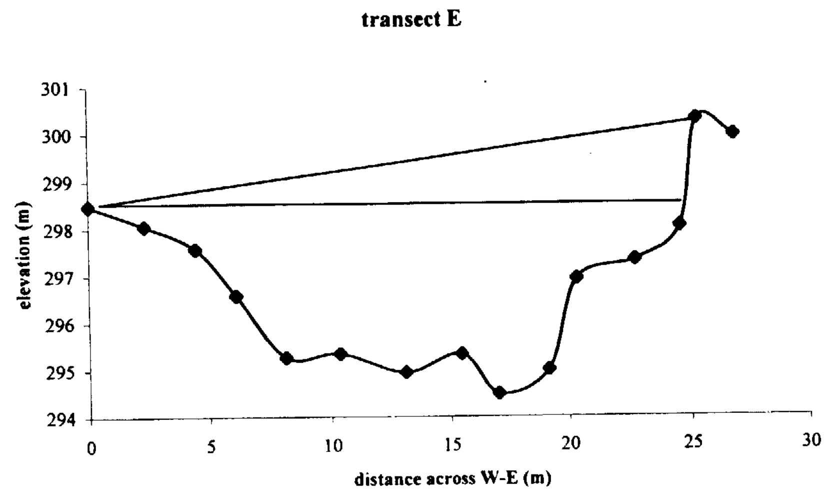


APP. I

Figure 4b

Generals Slide Cross-sections





App. 1

Figure 4c

Generals Slide Cross-sections

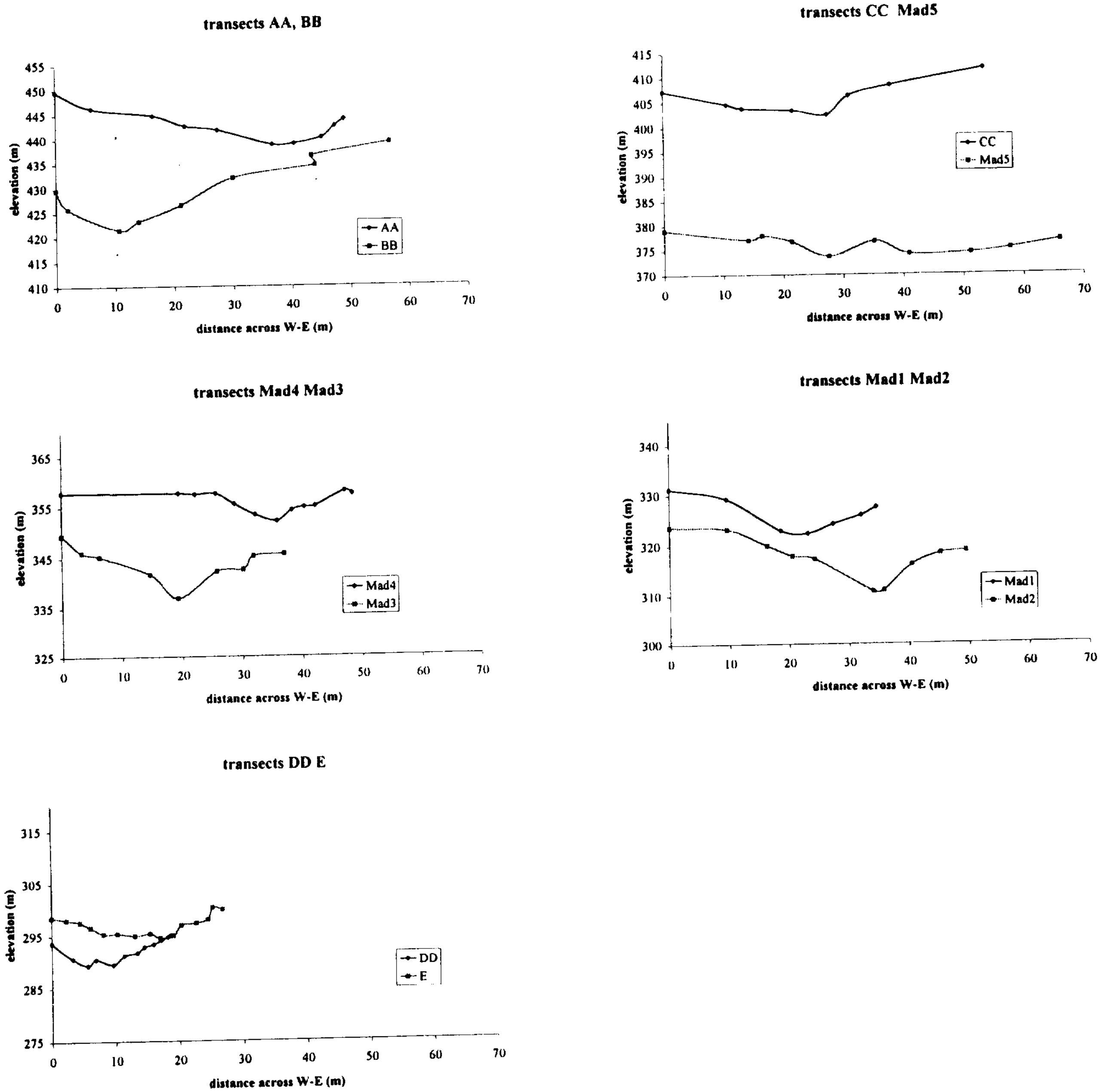


Figure 5 Same Scale Generals Slide Cross-sections

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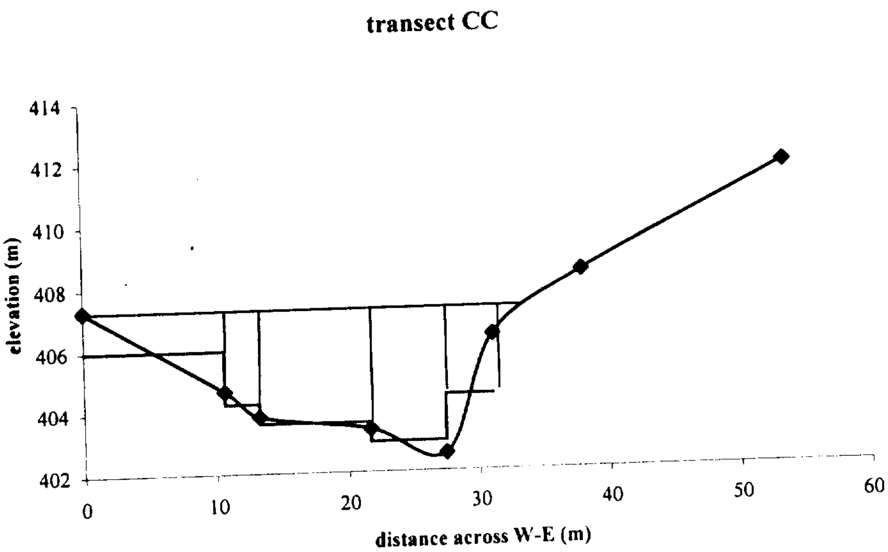
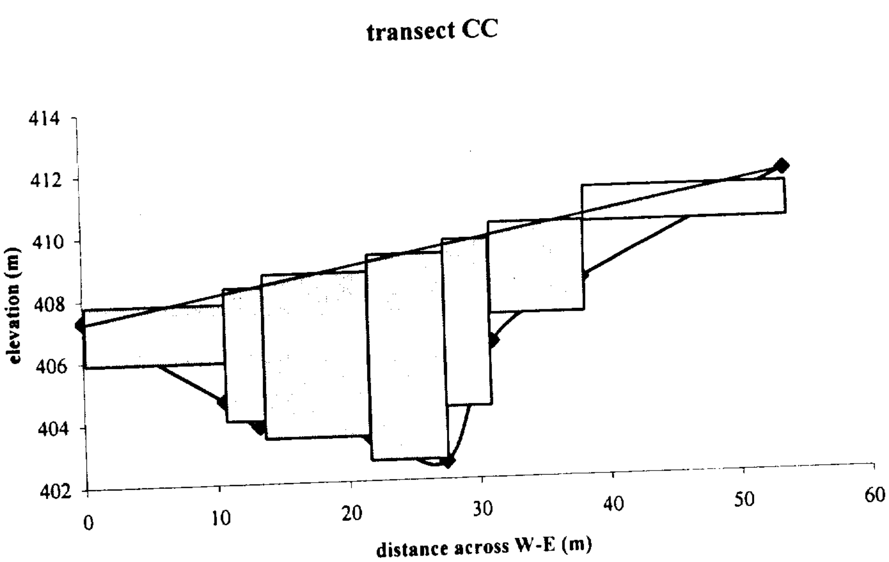


A. MIMIMUM CASE



B. MAXIMUM CASE

Figure 6

Area estimation from cross-sections

App. 1

Table 1a. Generals Slide　　　　Minimum Case　　　　Modeling Data

MADISON DATA (GENERALS SLIDE) AS OF 3/27/00

Transect	downstream position (m)	elevation (m)	trended slope (deg)	width (m)	MINIMUM weighted av. thickness (min) (m)	Area av. A (min) (m2)	Modeling results Cn/Co
AA	473	438	15.17	32.51	2.72	88.5	1
BB	535	421	14.05	28.01	1.83	51.3	0.475209
CC	627	402	12.51	31.12	2.85	88.6	0.867806
Mad5	808	374	9.9	44.68	1.62	72.5	0.354173
Mad4	905	352	8.75	21.54	2.77	59.6	0.485827
Mad3	981	344	7.98	33.69	3.12	105.2	0.663468
Mad1	1084	323	7.1	25.09	2.65	66.6	0.399199
Mad2	1173	311	6.5	28.93	3.39	98.1	0.567643
E	1361	294	5.75	17.17	2.39	41.1	0.229254
DD	1404	290	5.67	24.55	2.23	54.7	0.243351
						k=	0.5

Used polynomial 3-order fit to calculate slope
y=-5.6717E-8x3 + 0.0002544x2 - 0.472968x + 613.03
R2 = 99.8107

Based on horizontal flow surface; thicknesses are from weighted average depths (Area/width)

App 1

Modeling Data

Table 1b. Generals Slide

Maximum Case

MADISON DATA (GENERALS SLIDE) AS OF 3/27/00

Transect	downstream position (m)	elevation (m)	trended slope (deg)	dth (max) (ı	MAXIMUM weighted av. thickness (max) (m)	Area av. A (max) (m2)	Modeling results Cn/Co
AA	473	438	15.17	49.02	3.81	186.6	1
BB	535	421	14.05	41.41	3.07	127.1	0.616944
CC	627	402	12.51	53.61	3.05	163.3	0.619889
Mad5	808	374	9.9	66.1	1.91	126.4	0.271081
Mad4	905	352	8.75	21.54	2.77	59.6	0.238859
Mad3	981	344	7.98	37	4.54	167.9	0.599651
Mad1	1084	323	7.1	34.72	3	104.4	0.278187
Mad2	1173	311	6.5	39.84	4.15	165.2	0.443358
E	1361	294	5.75	18.69	2.82	52.8	0.150739
DD	1404	290	5.67	25.28	3.04	77	0.193514

k= 0.5

Used polynomial 3-order fit to calculate slope
y=-5.6717E-8x3 + 0.0002544x2 - 0.472968x + 613.03
R2 = 99.8107

Based on tilted flow surface; thicknesses are from weighted average depths (Area/width)

APP 1

TABLE 2. GENERALS DEBRIS FLOW: TRANSECT NOTES TABLE

Transect	Notes
AA	Just below junction of two forks. Scoured bed. High "splash" on river left.
BB	Scoured bedrock bed.
CC	Scoured bedrock bed.
Mad5	Flow separation, possible mass loss above this point.
Mad4	Before/atop boulder dam. Well-constrained bedrock channel. No clear field evidence defining right flow edge.
Mad3	Well-constrained bedrock channel. Definition of right flow edge problematic.
Mad1	Well-constrained bedrock channel. Channel turns, emerges from trees. Very good flow depth/edge evidence.
Mad2	Deep incised V shaped clay-rich soil channel. Very good flow depth/edge evidence.
E	V shaped clay-rich soil channel. Some evidence for deposition. Very good flow depth/edge evidence.
DD	V shaped clay-rich soil channel. Some evidence for deposition.

APP 1

TOPOGRAPHIC DATA FOR DEBRIS FLOWS - IMPLICATIONS FOR PLANETARY MODELING STUDIES.

[1]Bulmer, M.H., [2]Peitersen M.N., [3]Barnouin-Jha,O.S., [1]Johnston, A.K., and M. [1]Bourke, [1]Center for Earth and Planetary Studies, Smithsonian Institution, Washington DC 20560-0315 (mbulmer@ceps..nasm.edu), [2]Proxemy Research, 20528 Farcroft Lane, Laytonsville, MD 20882, [3]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723-6099.

Introduction: Debris flows and other forms of mass movement are significant geomorphic agents on the terrestrial planets. Viking images revealed deposits that have been interpreted to be similar to terrestrial debris flows [1]. The term debris flow is used to denote a viscous to highly fluid form of rapid mass movement of granular solids, (vegetation and air) with flow properties that vary with water content, sediment size and sorting of particles. We have obtained high-precision topographic profiles and performed a sedimentological study over a debris flow near Graves Mill (38.24°N, 78.23°W) in Madison County, Virginia. Use of an empirical model in conjunction with these data constrain to first order the flow behavior during the emplacement of the Graves Mill debris flows, and provide a method to interpret debris flow emplacement on Mars [e.g. 1].

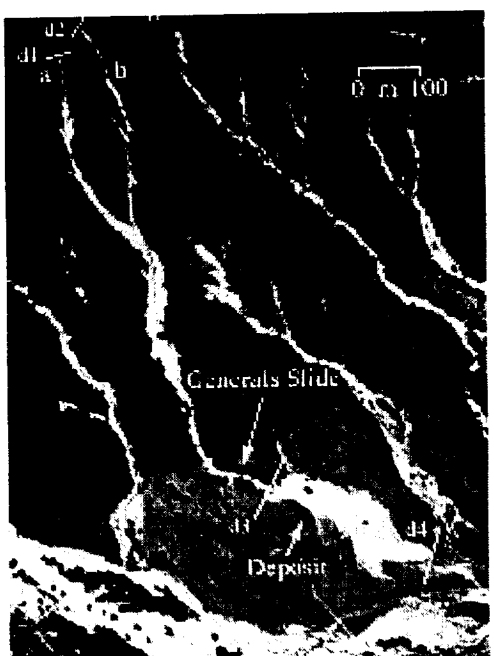


Fig. 1. Generals Slide at Graves Mills, Virginia.

Field Site: An intense storm on June 27, 1995 centered over an area of about 75 km^2 triggered hundreds of rock, debris and soils slides from the steep hillsides of the Shenandoah Mountains [2]. Most of these slope failures transformed into debris flows [Fig. 1]. During approximately sixteen hours as much as 770 mm of rain fell in the area of maximum storm intensity and probably ~640 mm fell within a five-hour period over small areas [2]. The area is underlain by mostly granitic quartzofeldspathic rocks [3]. Surface weathering has turned this rock into loose friable soils with substantial quartz sand and clay sitting on top of the coherent bedrock. Colluvium formed from soil creep and slope wash overlays some of the steeper slopes (slope >10°). Meters of weathered residual materials overlie bedrock at the base of steep slopes.

To investigate the emplacement mechanism of debris flows in the region we collected GPS topographic profiles, and rock/soil samples on the 'Generals slide' [Fig. 1]. During the topographic survey, slope angles, flood-lines and boulder positions were also measured. The geometry of the channel both along and across the stream profile were characterized using one long transect from the debris fan up to the source region, and ten across channel profiles where ever it was possible to match up high-water marks on the left and right channel banks.

Field results: Geomorphic evidence indicates that more than one pulse formed the Generals slide debris flow deposits. The actual number is unknown, but there are several drainage channels which feed into the main channel [Fig 1.]. The distance from the top of channel 'a' (d1) of the 'Generals slide' to the edge of the treeline (d3) is 919 m and from the top of channel 'b' (d2) to the same location (d3) is 925 m. The elevation change over this length is 329.3 m. There are many breaks of slope and good evidence for superelevation on the outside of channel bends. At the source area to channel 'a' the failure scarp is only 14.7 m wide and 0.7 m to 1.0 m deep on a 48° slope. This initial failure appears to have been a shallow translational soil and rock slide. The channel the debris flow traveled down contains a range of coarse-sized materials with boulders up to 10 m on a side, some of which are from a prior event but are mantled by clasts from the 1995 event. Once the debris flow emerged from the channel near the treeline and out onto the fields [Fig. 1] it deposited a range of material sizes from blocks and boulders down to clay and silt. Based on measurements on an air photo the main deposit L (d3 to d4) is 311 m long and 93 m at its widest W [Fig. 1]. It covered an area 0.02 km^2. Eyewitness accounts estimate the thickness T of the deposits to have been approximately 1 m. Using L, W and T we have derived a first-order volume estimate of 21,960 m^3 of deposited material. This is significantly greater than that which could have been derived from the source areas 'a' and 'b' alone.

App 1. A

The Empirical Model: Simple empirical volumetric flow rate models provide preliminary insight into the behavior and rheology of the Generals slide. Such models have been used to study diverse mass movements of geologic materials, including lahars [4], mud flows [5], glaciers [6], and lava flows [e.g. 7,8]. In this study, we use a very general form for flow rate

$$Q = uA = \left[\frac{gh\sin\theta}{C}\right]^k A \qquad (1)$$

where A is the cross-sectional area of the flow, g is gravity, θ is the underlying slope, h is the flow thickness, and C and k are empirically derived parameters. The variable $C = 1/Fr$ when $k = 0.5$. The Froude number Fr relates inertial to gravitational forces and thereby C is indicative of all the other forces relative to gravity that influence the downhill progress of the debris flow.

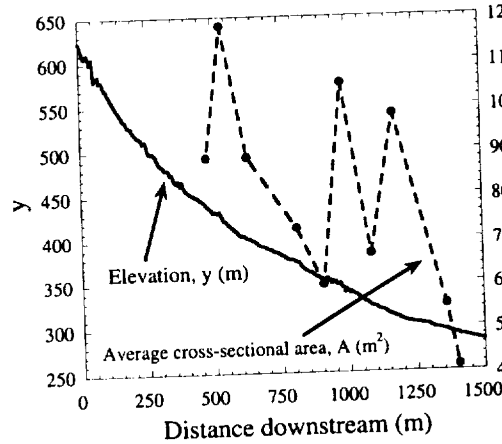
We can use the morphometry of the debris flows to estimate C. As in other studies of this type [e.g. 8], we maintain $k = 0.5$ to ensure a dimensionless C. In addition, we assume a constant Q. Using our morphometric data set, we estimate changes in C at any point x_n along the debris channel relative to a reference point x_0:

$$\frac{C_0}{C_n} = \frac{Fr_n}{Fr_0} = \left(\frac{A_0}{A_n}\right)^2 \frac{h_0 \sin\theta_0}{h_n \sin\theta_n} \qquad (2)$$

Inferences about processs along the channel can be made by comparing C to morphologic features downstream, as well as to parameters found for other debris flows.

Results of model application/discussion: Application of equation (2) revealed large changes in Fr, as shown in figure 2. Initially decreasing Fr are consistent with a debris flow becoming less fluid possibly due to entrainment of eroded material. Large variation at around 1000 m occurs near rapid slope and cross-sectional area changes. High values of Fr from the 1000 m point to the flow's end are most likely overestimates in C caused by the constant Q assumption. A drop in Q due to loss of volume in the depositional zone is expected, and would result in increasing Fr as shown by figure 2. The model estimates for flow speed along the channel will be tested against superelevation data as well as observed blocks sizes on the flow margins. Such comparisons will better constrain the C, Fr and Q along the Generals slide, thereby improving our preliminary understanding of the flow rheology as it moves downslope.

Planetary implications: These preliminary analyses indicate how high resolution topographic data may provide a first step towards constraining the dynamics and rheology of a debris flows. The block size data, the superelevation analysis and the sedimentary analyses along the channel of the flow provide additional information that will further constrain the flow dynamics as expressed in the empirical model used here.



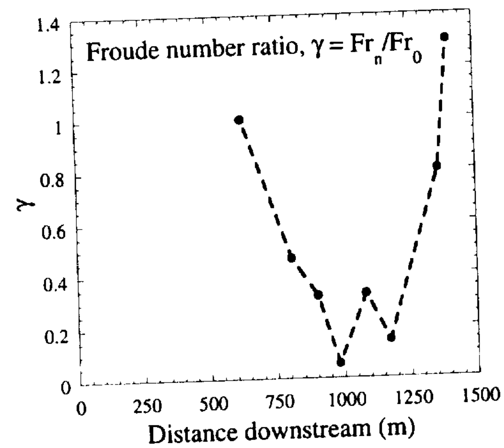


Fig. 2. Variations in elevation, cross-sectional area A and Fr_n/Fr_o with distance downstream.

In addition, this information can be linked to more sophisticated models that allow estimating the amounts of fluid and solid [e.g. 9] in a debris flow, information of particular importance to understanding the size and evolution of water reservoirs on Mars. On Mars, topographic data can be obtained from MOLA, while sedimentary data may be obtained through thermal inertia obtained at a debris flow using TES data, as well as high resolution MOC imagery.

References: [1] Carr, M.H., (1996) *Water on Mars, 229pp.* [2] Wieczorek, G.F., et al., (1996) USGS Open File Rep. 96-13. [3] Allen, R.M. (1963) Virginia Div. Min. Res. 78, 102. [4] Weir, G.J., (1982) *New Zealand J. Sci. 25,* 197-203. [5] Gol'din, B. and L.S. Lyubashevskiy (1966) *Trudy Ukr. NIGMI 60,* 73-75. [6] Paterson, W.S.B. (1969) Physics of Glaciers, 250 pp. [7] Baloga, S.M, et al., (1995), *J. Geophys. Res. 100,* 24,509-24519. [8] Baloga, S.M., et al. (1998) *J. Geophys. Res. 103,* 5133-51421. [9] Iverson, R. M. (1997) *Rev. Geophs.* 35, 3, 245-297.

App 1. A

ABSTRACT 1820 TOPOGRAPHIC DATA FOR DEBRIS FLOWS - IMPLICATIONS FOR PLANETARY MODELING STUDIES

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Introduction

Debris flows and other form of mass movement are significant geomorphic agents on the terrestrial planets. Viking images revealed deposits that have been interpreted to be similar to terrestrial debris flows [1]. The term debris flow is used to denote a viscous to highly fluid form of rapid mass movement of granular solids, (vegetation and atmosphere) with flow properties that vary with water content. We have obtained high-precision topographic profiles and performed a sedimentological study over a debris flow near Gravel Mill (38.2 degrees N, 78.23 degrees W) in Madison County, Virginia. Use of an empirical model in conjunction with these data constrain to first order the flow behavior during the emplacement of the Graves Mill debris flow and provide a method to interpret debris flow emplacement on Mars [e.g., 1].

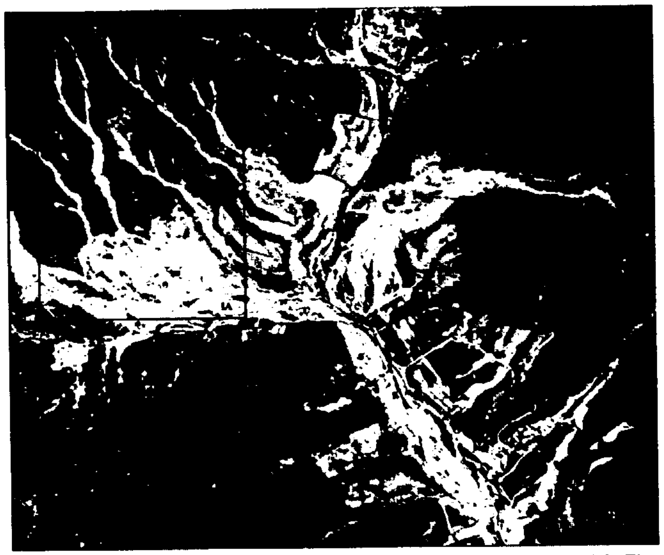

Figure 1. Color infrared aerial photograph of the Gravel Mill area, Madison County taken on 22 August 1995 approximately two months after the June 27th storm which triggered hundreds of rock, debris and soil slides. 1:18,000 scale.

Inset 1A. The Generals slide at Graves Mill. Image is from the same date as Fig. 1.

Field Site

An intense storm on June 27, 1995 centered over an area of about 75 square kilometers triggered hundreds of rock, debris and soil slides from the steep hillsides of the Blue Ridge Mountains [2]. Most of these slope failures transformed into debris flows [Fig. 1]. During approximately sixteen hours as much as 770 mm of rain fell in the area of maximum storm intensity and probably ~640 mm fell within a five-hour period over small areas [2]. The area is underlain by mostly quartzofeldspathic rocks [3]. Surface weathering has turned this rock into loose friable soils with substantial quartz sand and clay sitting on top of coherent bedrock. Colluvium formed from soil creep and slope wash overlays some of the steeper slopes (> 10 degrees). Meters of weathered residual materials overlie bedrock at the base of steep slopes.

Surface Topography Data Collection

To investigate the emplacement mechanism of debris flows in the Graves Mill region we collected GPS topographic and rock/soil samples on the Generals slide [see Figure 1, Inset 1A]. The main debris flow channel was surveyed using a Trimble Total Station 4800, which consists of two GPS receivers that work in tandem. This equipment uses carrier-phase differential processing for 1 cm horizontal real-time accuracy. One receiver remains fixed on a tripod at a known location during the survey [Fig. 2]. The location of this receiver was determined to an accuracy of 1-2 m using a Trimble ProXRS GPS unit using satellite-based differencial correction. This base station was then used as the reference point for all subsequent surveys. The roving Trimble 4800 receiver used for data collection is mounted on a pole 1.8 m in length. This pole allows the survey team to determine positions even in the small spaces between blocks, so the topography can be adequately characterized. A radio link, provided by a 25 W UHF radio at the base station, is constantly maintained for real-time differential correction. While conducting transects down the main channel, a 3-D point was collected approximately every 3m. We obtained 1 cm horizontal and 2 cm vertical accuracy per point to about 1000m up from the lower end of the channel, until we encountered difficulties in satellite coverage due to screening by the tree canopy. Beyond that point the accuracy was only about 20-40cm. We successfully collected data up to the top of the main channel, about 1600m.

In addition to the main channel transect we also measured 10 cross-channel profiles [Fig. 2] using a laser rangefinder (Laser Atlanta Advantage CL) connected to the Trimble ProXRS. A 3-D point was collected every 3-6 m with an accuracy of 10-15 cm. The position of each cross-channel profile relative to the main channel was determined to an accuracy of about 1 m by locating points that had been surveyed previously using the Trimble 4800. Using available air photos and field observations, the attempt was made to conduct transects where a measure of depth for the 1995 event could be determined as well as an across-channel profile. Geomorphic signatures of the 1995 event that we used most frequently in determining debris flow depths were tree, soil and rock materials that had been pushed up against base of tree trunks on the edge of the channel. Measurement of minimum depths were also collected where fines from the 1995 event had been deposited on top of large boulders. At some locations (transects BB, CC, Mad4, Fig. 3) it was difficult to determine the edge of the 1995 event. At these locations we extended the profile out to the first available geomorphic indicator for the absence of the gound having been disturbed by the 1995 event. Using this procedure we attempted to obtained the maximum possible width measurement.

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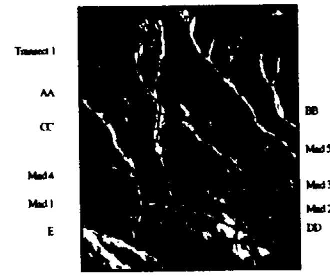

Figure 2. Transect lines both along and across the Generals slide channel are shown in yellow. Underlying air photo is from 24th March 1997.

Figure 3. Along channel profile (Transect 1, Fig. 2) showing the change in elevation from the source region out to the main depositional fan resulting from the 1995 event.

Field results:

Geomorphic evidence indicates that more than one pulse formed the Generals slide debris flow deposits. The actual number is unknown, but there are several drainage channels which feed into the main channel [Fig 1, Inset 1A]. The distance from the top of channel 'a' (d1) of the 'Generals slide' to the edge of the treeline (d3) is 919 m and from the top of channel 'b' (d2) to the same location (d3) is 925 m. The elevation change over this length is 329.3 m [Fig. 3]. There are many breaks of slope and good evidence for superelevation on the outside of channel bends. At the source area to channel 'a' the failure scarp is only 14.7 m wide and 0.7 m to 1.0 m deep on a 48° slope. This initial failure appears to have been a shallow translational soil and rock slide. The channel the debris flow traveled down contains a range of course-sized materials with boulders up to 10 m on a side, some of which are from a prior event but are mantled by clasts from the 1995 event. Once the debris flow emerged from the channel near the treeline and out onto the fields [Fig. 1] it deposited a range of material sizes from blocks and boulders down to clay and silt. Based on measurements on an air photo the main deposit L (d3 to d4) is 311 m long and 93 m at its widest W [Fig. 1, Inset 1A]. It covered an area 0.02 squarekm. Eyewitness accounts estimate the thickness T of the deposits to have been approximately 1 m. Using L, W and T we have derived a first-order volume estimate of 21,960 m cubed of deposited material. This is significantly greater than that which could have been derived from the source areas 'a' and 'b' alone.

The Empirical Model:

Simple empirical volumetric flow rate models provide preliminary insight into the behavior and rheology of the Generals slide. Such models have been used to study diverse mass movements of geologic materials, including lahars [4], mud flows [5], glaciers [6], and lava flows [e.g. 7,8]. In this study, we use a very general form for flow rate

$$Q = uA = [gh \sin\theta / C]^k A \quad (1)$$

where A is the cross-sectional area of the flow, g is gravity, θ is the underlying slope, h is the flow thickness, and C and k are empirically derived parameters. The flow is divided into segments using the across channel profiles

Cross-sectional area is determined by dividing. The variable $C = 1/Fr$ when $k = 0.5$. The Froude number Fr relates inertial to gravitational forces and thereby C is indicative of all the other forces relative to gravity that influence the downhill progress of the debris flow.

We can use the morphometry of the debris flows to estimate C. As in other studies of this type [e.g. 8], we maintain $k = 0.5$ to ensure a dimensionless C. In addition, we assume a constant Q. Using our morphometric data set, we estimate changes in C at any point x_n along the debris channel relative to a reference point x_0:

(2)

Inferences about processs along the channel can be made by comparing C to morphologic features downstream, as well as to parameters found for other debris flows.

Results of model application/discussion:

Application of equation (2) revealed large changes in Fr, as shown in figure 2. Initially decreasing Fr are consistent with a debris flow becoming less fluid possibly due to entrainment of eroded material. Large variation at around 1000 m occurs near rapid slope and cross-sectional area changes. High values of Fr from the 1000 m point to the flow's end are most likely overestimates in C caused by the constant Q assumption. A drop in Q due to loss of volume in the depositional zone is expected, and would result in increasing Fr as shown by figure 2. The model estimates for flow speed along the channel will be tested against superelevation data as well as observed blocks sizes on the flow margins. Such comparisons will better constrain the C, Fr and Q along the Generals slide, thereby improving our preliminary understanding of the flow rheology as it moves downslope.

Planetary implications:

These preliminary analyses indicate how high resolution topographic data may provide a first step towards constraining the dynamics and rheology of a debris flows. The block size data, the superelevation analysis and the sedimentary analyses along the channel of the flow provide additional information that will further constrain the flow dynamics as expressed in the empirical model used here. In addition, this information can be linked to more sophisticated models that allow estimating the amounts of fluid and solid [e.g. 9] in a debris flow, information of particular importance to understanding the size and evolution of water reservoirs on Mars. On Mars, topographic data can be obtained from MOLA, while sedimentary data may be obtained through thermal inertia obtained at a debris flow using TES data, as well as high resolution MOC imagery.

References

[1] Carr, M.H., (1996) Water on Mars, 229pp. [2] Wieczorek, G.F., et al., (1996) USGS Open File Rep. 96-13. [3] Allen, R.M. (1963) Virginia Div. Min. Res. 78, 102. [4] Weir, G.J., (1982) New Zealand J. Sci. 25, 197-203. [5] Gol'din, B. and L.S. Lyubashevskiy (1966) Trudy Ukr. NIGMI 60, 73-75. [6] Paterson, W.S.B. (1969) Physics of Glaciers, 250 pp. [7] Baloga, S.M. et al., (1995), J. Geophys. Res. 100, 24,509-24519. [8] Baloga, S.M., et al. (1998) J. Geophys. Res. 103, 5133-51421. [9] Iverson, R. M. (1997) Rev. Geophs. 35, 3, 245-297.

Appendix

App 2

Investigating the physical factors controlling a debris flow – Implications for landscape evolution. Barnouin-Jha, O., M. Bulmer, M. Peitersen, M. Bourke and A. Johnston.

Detailed field work of a debris flow near Graves Mill (38.24N, 78.23W) in Madison County, Virginia, is combined with theoretical modeling to better constrain the most important physical factors controlling debris flow mechanics. Such work will allow improved characterization of debris flows and their effect on landscape evolution, and help interpret debris flow emplacement on other terrestrial planets (e.g., Mars).

An intense storm on June 27, 1995 triggered a substantial number of debris flows off the steep slopes of the Blue Ridge; we examined one of these in depth. The flow (hereafter denoted as the "Generals Slide") extends from an obvious source area (a translational slide scarp possessing a 48 degree slope) to a depositional fan approximately 1230 m downstream. Our data sets include: (1) high resolution GPS topography both along and across the channel; (2) extensive geomorphological descriptions of the channel pertinent to the debris flow; (3) super elevation data at various bends in the channel; (4) sedimentary profiles; (5) sedimentary analysis of matrix and boulders comprising the debris flow; (6) cohesion and internal friction of the soil at the debris flow's source, and (7) the plastic and liquid limits of the matrix.

In a previous study, the topographic data was input into a simple empirical volumetric flow rate model that provides preliminary insight into the behavior of the General slide. The results indicate qualitative correlations between the flow dynamics as expressed by this model with run-off input, local changes in slope, and sediment loss and gain. In the current work, we rigorously test these model results against quantitative information obtained from our fieldwork data for the debris flow speed, flow rheology, and sedimentary profiles. We also assess more sophisticated debris flow models that include both the measured topography and the rheological characteristics of the flow.

Appendix 3

Topographic Data for Debris Flows - Implications for Planetary Modeling Studies.

[1]Bulmer, M.H., [2]Peitersen, M.N., [3]Barnouin-Jha,O.S., [1]Johnston, A.K., and M. [1]Bourke, [1]Center for Earth and Planetary Studies, Smithsonian Institution, Washington DC 20560-0315 (mbulmer@ceps.nasm.edu), [2]Proxemy Research, 20528 Farcroft Lane, Laytonsville, MD 20882, [3]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723-6099.

Abstract. Debris flows and other forms of mass movement are significant geomorphic agents on the terrestrial planets. Viking images revealed deposits that have been interpreted to be similar to terrestrial debris flows [*Carr,* 1996]. However, many questions about the origin of these deposits can only be addressed through high-resolution imaging, topography and sedimentological data. The term debris flow is used to denote a viscous to highly fluid form of rapid mass movement of granular solids, (vegetation and air) with flow properties that vary with water content, sediment size and sorting of particles. We have obtained high-precision topographic profiles and performed a sedimentological study over a debris flow near Graves Mill (38.24°N, 78.23°W) in Madison County, Virginia. Use of an empirical model in conjunction with these data constrain to first order the flow behavior during the emplacement of the Graves Mill debris flows, and provide a method to interpret debris flow emplacement on Mars [*Carr,* 1996].

Introduction

An intense storm on June 27, 1995 centered over an area of about 75 km^2 triggered hundreds of rock, debris and soils slides from the steep hillsides of the Shenandoah Mountains [*Wieczorek et al.*, 1996]. Most of these slope failures transformed into debris flows (Figure 1). During approximately sixteen hours as much as 770 mm of rain fell in the area of maximum storm intensity and probably ~640 mm fell within a five-hour period over small areas [*Wieczorek et al.*, 1996]. Numerous geologic studies have been carried out on debris flows [*e.g.*, *Costa and Wieczorek*, 1987; *Iverson*, 1997], but many questions remain that need to be addressed using detailed field studies before possible debris flow features on Mars can be adequately examined. Historical debris flows have been reported all along the Appalachian Mountains, and stratigraphic evidence indicates that debris flows have been important geomorphic slope processes through the Quaternary [*Mills*, 1982; *Kochel and Johnston*, 1984]. An inventory of debris flow and flooding effects from the 1995 storm in Madison county was produced by the USGS [*Wieczorek et al.*, 1995, 1996; *Morgan et al.*, 1997]. The area is underlain by mostly granitic quartzo-feldspathic rocks [*Allen*, 1963]. Surface weathering has turned this rock into loose friable soils with substantial quartz sand and clay sitting on top of the coherent bedrock. Colluvium formed from soil creep and slope wash overlays some of the steeper slopes (slope >10°). Meters of weathered residual materials overlie bedrock at the base of steep slopes.

We chose to investigate the emplacement mechanism of one debris flow from the 1995 storm known as the "Generals slide" (Figure 1). We collected topographic profiles using global positioning (GPS) equipment, and rock/soil samples from both the "Generals slide" deposits and along the stream channel. During the topographic survey, slope angles, flood-lines and boulder positions were also measured.

In this paper, we consider the use of an empirical model in conjunction with the geomorphic observations and stratigraphic studies, to constrain to first order the emplacement of the "Generals slide" debris flow and hence a method to interpret debris flow emplacement on Mars. We first describe the techniques used to obtain the topographic dataset from the source area all the way out to the depositional fan of the "Generals slide". Profiles both along the channel and fan as well as at selected locations across the channel. The results from the fieldwork surveys are then described. These data are then used in the flow rate model. We validate the model-derived outputs by comparing them with our geomorphological and sedimentological observations. Finally, we assess the impact of these results to studies of possible Martian debris flows.

Surface Topography Data Collection

The main channel of the "General slide" was surveyed using a Trimble Total Station 4800, which consists of two GPS receivers that work in tandem. This equipment uses carrier-phase differential processing for 1 cm horizontal real-time accuracy. One receiver remains fixed on a tripod at a known location during the survey (Figure 2). The location of this receiver was determined to an accuracy of 1-2 m using a Trimble ProXRS GPS unit using satellite-based differential correction. This base station was then used as the reference point for all subsequent surveys. The roving Trimble 4800 receiver used for data collection is mounted on a pole 1.8 m in length. This pole allows the survey team to determine positions even in the small spaces between blocks, so the topography can be adequately characterized. A radio link, provided by a 25 W UHF radio at the base station, is constantly maintained for real-time differential correction. While conducting transects up the main channel, a 3-D point was collected approximately every 3 m. This spacing was determined in the field to adequately represent the topographic character of the channel profile and met the resolution requirements of the empirical model. For the transect up the channel (transect 1) we obtained 1 cm horizontal and 2 cm vertical accuracy per point to about 1000 m up from the lower end of the channel, until we encountered difficulties in satellite coverage due to screening by the tree canopy. Beyond that point, the accuracy was only about 20-40 cm. We successfully collected data up to the top of the main channel, about 1600m.

In addition to the main channel transect we also measured 10 cross-channel profiles (Figure 2) using a laser rangefinder (Laser Atlanta Advantage CL) connected to the Trimble ProXRS. A 3-D point was collected every 3-6 m with an accuracy of 10-15 cm. The position of each cross-channel profile relative to the main channel was determined to an accuracy of about 1 m by locating points that had been surveyed previously using the Trimble 4800. Using available air photos and field observations, the attempt was made to conduct cross-channel transects where a measurement of depth for the 1995 event could be determined as well as an across-channel profile. Geomorphic signatures of the 1995 event that we used frequently in determining debris flow depths were locations where tree, soil, and rock materials had been pushed up against the base of tree trunks on the edge of the channel. Measurements of minimum depths were also collected where fines from the 1995 event had been deposited on top of large boulders. At some locations (transects BB, CC, Mad4) it was difficult to determine the edge of the 1995 event. At these locations we extended the profile out to the first available geomorphic indicator for the absence of the ground having been disturbed by the 1995 event. Using this procedure we attempted to obtain the maximum possible width measurements.

Field results

Geomorphic evidence indicates that more than one pulse formed the Generals slide debris flow deposits and that these pulses were likely transitional between hyperconcentrated flow and debris flow. The actual number of pulses is unknown, but there are several drainage channels, which feed into the main channel (Figure 1). The distance from the top of channel 'a' (d_1) of the 'Generals slide' to the edge of the treeline (d_3) is 919 m and from the top of channel 'b' (d_2) to the same location (d_3) is 925 m. The elevation change over this length is 329.3 m. There are many breaks of slope and good evidence for superelevation on the outside of channel bends. At the source area to channel 'a' the failure scarp is only 14.7 m wide and 0.7 m to 1.0 m deep on a 48° slope. This initial failure appears to have been a shallow translational soil and rock slide. The channel the debris flow traveled down contains a range of coarse-sized materials with boulders up to 10 m on a side, some of which are from a prior event but are mantled by clasts from the 1995 event. Once the debris flow emerged from the channel near the treeline and out onto the fields (Figure 1) it deposited a range of material sizes from blocks and boulders down to clay and silt. Based on measurements on an air photo the main deposit L (d_3 to d_4) is 311 m long and 93 m at its widest W (Figure 1). It covered an area 0.02 km^2. Eyewitness accounts estimate the thickness T of the deposits to have been approximately 1 m. Using L, W and T we have derived a first-order volume estimate of 21,960 m^3 of deposited material. This is significantly greater than that which could have been derived from the source areas 'a' and 'b' alone.

The Empirical Model

Simple empirical volumetric flow rate models provide preliminary insight into the behavior and rheology of the Generals slide. Such models have been used to study diverse mass movements of geologic materials, including lahars [*Wier,* 1982], mudflows [*Gol'din and Lyubashevskiy,* 1966], glaciers [*Paterson,* 1969], and lava flows [e.g. *Baloga et al.,* 1995, 1998]. In this study, we use a very general form of the flow rate (Q):

$$Q = uA = [gh \sin \theta / C]^k A \tag{1}$$

where A is the cross-sectional area of the flow, u is the velocity, g is gravity, θ is the underlying slope, h is the flow thickness, and C and k are empirically derived parameters. Assuming a steady state and a constant flux:

$$Q_0 = [gh_0 \sin \theta_0 / C_0]^k A_0 = [gh_n \sin \theta_n / C_n]^k = Q_n \tag{2}$$

Solving for C, the flow resistance coefficient, yields

$$[C_n/ C_0] = [A_n/ A_0]^{1/k} / [(h_n \sin \theta_n)/ (h_0 \sin \theta_0)] \tag{3}$$

Given the morphometry of the debris flow, and a known value of k, this equation can be used to calculate relative changes in rheology (as expressed by variations in C) from some arbitrary initial reference point.. The typical value k = 0.5, employed in numerous previous studies type [e.g. *Bologa et al.*, 1998], is adopted as a mathematical convenience. However, initial attempts to estimate k imply that the value for the Generals slide is somewhere in this vicinity.

Results of model application/discussion

Application of equation (3) revealed moderate changes in C, as shown in Figure 3. A decrease in C with distance implies increased fluidity, consistent with the debulking of the debris flow by additional surface runoff. Small-scale topographic effects may cause deviations from this trend. A comparison of the flow profile to the modeling results (Figure 3) reveals positional correlations between repeated local slope changes and variations in C, in some cases. Surface roughness, nature of the bed, and flow/bed interactions (erosion, deposition, etc.) as well as local variations in volume (loss from overbanking, increase from tributary rills), may be responsible for the remaining variations. These factors, which, can be best constrained by field observations, will be subjects of future study.

Planetary implications

These preliminary analyses indicate how high resolution topographic data may provide a first step towards constraining the dynamics and rheology of a debris flows. Sufficiently accurate elevations, traditionally lacking for planetary features, are currently available for Mars via the MOLA data. However, topographic data alone is insufficient to adequately understand the dynamics of the flow. The block size data, the superelevation analysis and the sedimentary analyses along the channel of the flow, as well as detailed field observations, provide the additional information that will further constrain the flow dynamics as expressed in the empirical model used here. Such information will largely be lacking for planetary debris flows; however, judicious use of additional data sets such as TES and MOC, as well as comparison to appropriate terrestrial analogs, may be used to constrain Martian flows.

Our field data shows the complex processes involved in the debris flows. In future work, this information will be linked to more sophisticated models that allow estimating the amounts of fluid and solid [e.g. *Iverson,* 1997] in a debris flow, information of particular importance to understanding the size and evolution of water reservoirs on Mars. This work provides a foundation for analyzing existing MOC, MOLA, TES and Viking data over proposed Martian debris flows.

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FIGURE CAPTIONS:

Figure 1. Subscene from air photo of the Graves Mill area, taken 22 August 1995, several months after the debris flow event. Depositional fan of Generals slide is still clearly evident.

Figure 2. Field survey transects, overlaid on air photo from 24 March 1997.

Figure 3. Results of application of empirical model to Generals slide data. Relative change in C is overlaid on a plot of transect 1.

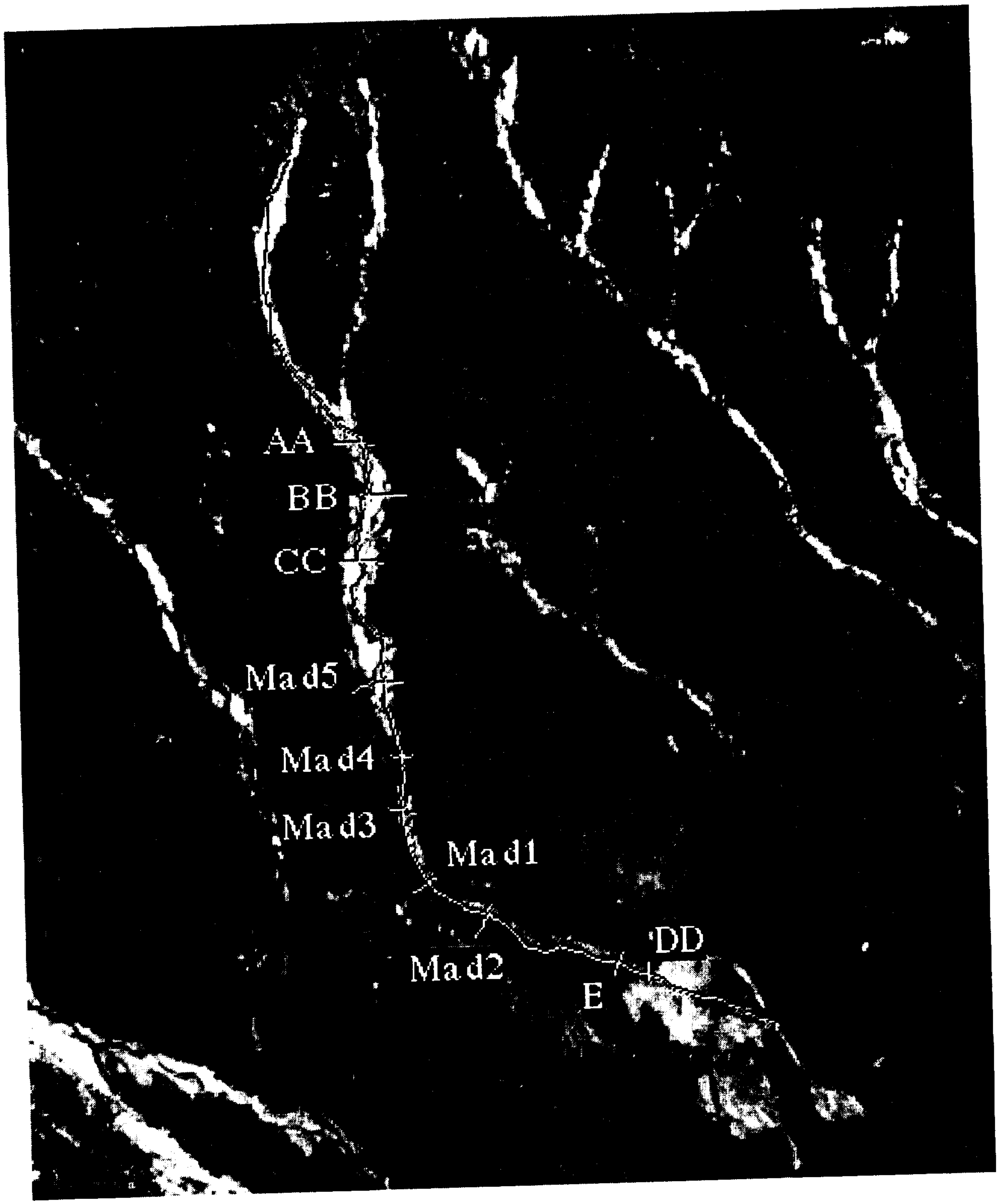
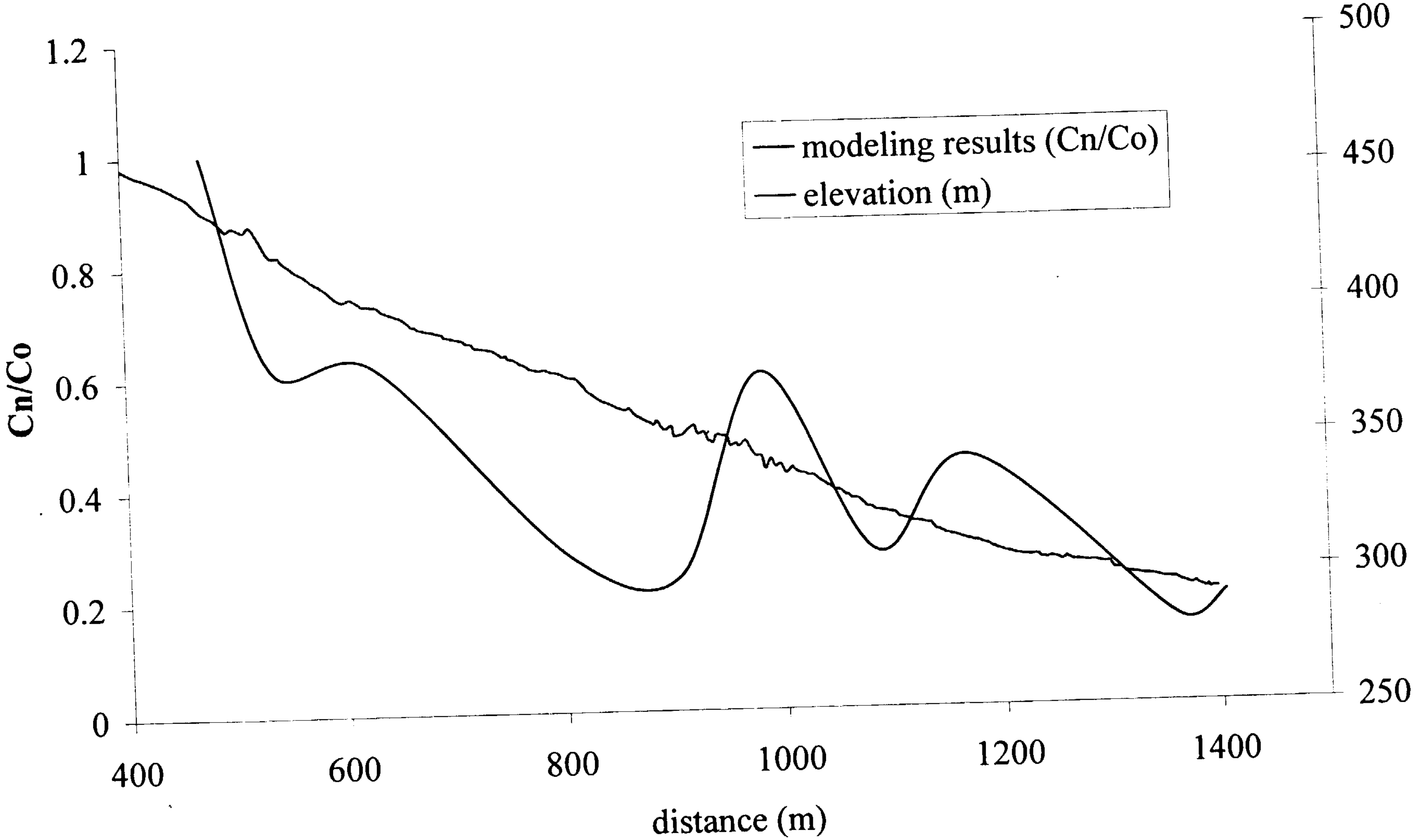


Figure 2

Appendix 4



Appendix 4

Figure 3

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Report Documentation Page

1. Report No. TOPO-99-012	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Response of lahars and lava flows to topographic changes		5. Report Date March 31, 2000
		6. Performing Organization Code
7. Author(s) Dr. Stephen M. Baloga		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address Proxemy Research 20528 Farcroft Lane Laytonsville, MD 20882		11. Contract or Grant No. NAS5-99182
		13. Type of Report and Period Covered Final Report 3/31/00
12. Sponsoring Agency Name and Address NASA/GSFC Greenbelt, MD 20771		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract This report describes research directed toward understanding the response of volcanic lahars and lava flows to changes in the topography along the path of the flow. We have used a variety of steady-state and time-dependent models of lahars and lava flows to calculate the changes in flow dynamics due to variable topography. These models are based on first-order partial differential equations for the local conservation of volume. A global volume conservation requirement is also imposed to determine the extent of the flow as a function of time and the advance rate. Simulated DEMs have been used in this report.

17. Key Words (Suggested by Author(s)) lahar modeling, lava flow modeling, variable topography	18. Distribution Statement

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages	22. Price

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